TM-225
0400

RADIATION DETECTOR SYSTEM FOR THE MAIN RING

L. C. Teng

March 12, 1970

Radiation detectors installed in the main ring tunnel to sense beam losses will serve as diagnostic devices during tune-up, and as monitoring and fault-detecting devices perhaps interlocked to trigger the beam abort system during normal operation.

Beam Loss Mechanisms

Probable beam loss mechanisms in the main ring are listed below:

A. Injection

A.1. Steering error

Field and alignment errors of the bending (septum) and kicker magnets impart to the injected beam a residual coherent vertical oscillation which may be too large for the aperture.

A.2. Kicker timing

Timing errors or too slow a rise and fall of the kicker magnet will impart improper deflections to beam bunches at either end of a booster pulse. Again, the resulting coherent vertical oscillation may be too large for the aperture.

A.3. Bunch matching

The phase and energy of an injected beam bunch should put it at the center of an RF bucket. A certain amount of error is tolerable and can be reduced by damping devices. But if the initial error is too large it will result in beam loss.

B. Orbit and Stability (transverse)

B.1. Closed-orbit distortion

Imperfections of the ring magnets and excitation of transmission line modes in the magnet circuit will lead to closed orbit distortions which, if excessive, will cause the beam to strike the aperture.

B.2. Betatron oscillation resonances

Imperfections of the ring magnets and transverse space charge forces* may move the betatron frequencies of the beam onto a resonance. This results in a rapid (a few revolutions) growth of the amplitude of incoherent oscillations.

B.3. Excitation of betatron oscillations

Under certain conditions the out-of-phase component of the space charge forces* will excite coherent oscillations. The typical growth time is in the millisecond range.

C. RF Tracking and Stability (longitudinal)

C.1. Frequency tracking error

*Space charge forces here include: (a) forces between protons in the beam, (b) forces between the beam and its image charges and currents, and (c) forces between the beam and ions from ionization of the residual gas.

This error causes the beam to deviate horizontally from the center of the vacuum chamber. Beam loss to the aperture may occur if the deviation is too large.

C.2. RF noise and voltage program error

These may cause spillage of the beam out of RF buckets at any time during the acceleration cycle.

C.3. Beam cavity loading

Since the ring is not uniformly filled with beam, especially during injection, the transient beam loading on the cavities is rather severe. If this is not adequately compensated by the fast feed-back loop it may cause spillage of beam bunches at the beginning of a booster pulse.

C.4. Improper transition crossing

Errors in the RF phase jump at transition induce coherent phase oscillations. In addition, mismatch in crossing transition due to space charge forces leads to a coherent bunch shape oscillation. Either oscillation may have an amplitude too large for the bucket.

D. Extraction

Alignment and field errors in the extraction transport (septum) elements may cause excessive beam loss on the septa of these elements.

E. Miscellaneous

E.1. Physical obstructions

Physical obstructions left inadvertently in the aperture will generally destroy the beam.

E.2. Gas scattering

General or local poor vacuum in the ring will cause beam loss through nuclear and multiple Coulomb scattering by residual gas. This loss is most prominent during injection.

E.3. Beam abort and scraper systems

Beam loss on these systems, though controlled, should also be monitored.

The characteristics of the beam loss due to these mechanisms are given in the following table:

Mechanism	Horizontal or Vertical(†)	Location of Occurrence(*)	Time of Occurrence	Duration of Beam Loss(#)
A.1.	V	kicker magnet and/or aperture blocks	injection	10^{-6} sec (Booster pulse length)
A.2.	V	kicker magnet and/or aperture blocks	injection	10^{-8} sec (RF bunch length)
A.3	H	aperture blocks	injection	10^{-3} sec (phase oscillation period)
B.1.	H or V	aperture blocks	injection (1st turn)	10^{-6} sec (Booster pulse length)
			acceleration	10^{-4} sec (magnet response time)
B.2	H or V	aperture blocks	anytime	10^{-5} sec (revolution period)
B.3	V (or H)	aperture blocks	anytime	10^{-3} sec (growth time)

-cont.-

Mechanism	Horizontal or Vertical(†)	Location of Occurrence(*)	Time of Occurrence	Duration Beam Loss(#)
C.1.	H	aperture blocks	anytime	10^{-4} sec (magnet response time)
C.2.	H	aperture blocks	anytime	10^{-3} sec (phase oscillation period)
C.3.	H	aperture blocks	injection & initial acceleratn.	10^{-3} sec (phase oscillation period)
C.4.	H	aperture blocks	shortly after transition	10^{-3} sec (phase oscillation period)
D.	H	extraction elements	extraction	1 sec (length of extraction)
E.1.	H and V	location of obstruction	injection	10^{-6} sec (Booster pulse length)
E.2.	H and V	all around ring but mostly aperture blocks	injection	$>10^{-5}$ sec (>revolution period, depending on pressure)
E.3.	V (abort) H or V (scraper)	beam stoppers of the respective systems	anytime when aborting or scraping	10^{-5} sec (revolution period) 10^{-3} sec (scraping time)

(#) This column gives order-of-magnitude estimates to establish only rough time scales. The features governing the time scales are given in parentheses.

(*) When the beam strikes a physical target in the ring the radiation is generally limited to within 1/4 betatron oscillation wave length (about 1 cell) downstream of the point of impact. This column gives possible locations of impact.

We assume that aperture limiting blocks are installed in all medium straight sections. In addition, the extraction septum forms an outer horizontal aperture limit and the injection septum forms an upper vertical aperture limit. These septa are included as aperture blocks.

Because of the ever-present closed-orbit distortions most likely the beam will strike only one of the aperture blocks--the one nearest to the closed orbit.

Only in the case of E.2. when the target is the residual gas do we get radiation spread all around the ring.

(†) This column gives the lateral position of the point of impact relative to the center of the ring aperture. The radiation produced will, of course, spread both vertically and horizontally.

The maximum total beam loss allowable for the main ring is <0.1% of full design beam = 5×10^{10} p/pulse. Considering the numbers of possible mechanisms and locations of beam loss it is reasonable to require a detection sensitivity corresponding to a loss of 10^9 protons at one time and at one location. The level of radiation produced is, to first approximation, dependent only on the energy content in the beam striking the target. At injection, 10^9 protons have an energy content of 1.3 Joules. We shall, therefore, set as the design criterion a detector sensitivity corresponding to about 1 Joule of beam loss.

Radiation Detectors

Only simple and inexpensive radiation detectors are considered here.

A. Ionization Chamber

The ionization chamber has the advantage of being highly reliable and stable, having a low noise level, and suffering no radiation damage. On the other hand it is relatively poor in sensitivity and response time. The response time is limited by the ion collection time which for an air-filled chamber is roughly given by:

$$\tau(\mathrm{sec}) \cong 0.4 \frac{d(\mathrm{cm})p(\mathrm{atm})}{E(\mathrm{V/cm})}$$

where p = pressure

d = plate separation

E = electric field between plates

To get a 1 μsec ion collection time at, say, 1 atm pressure and a plate voltage of 1000 V one needs a plate separation of 0.05 cm which is completely impractical.

The sensitivity in terms of total charge collected is roughly proportional to the active volume and the pressure of the chamber and to the energy content of the beam striking the target. The proportionality constant depends on the chamber gas, the relative position of the chamber to the target, and the geometry of the shielding matter in between; and is extremely difficult to estimate without extensive computation. For our geometry with air chamber an order-of-magnitude estimate based on measurements performed by the Radiation Physics Section at the ANL ZGS gives:

$$q \sim 10^{-11} \text{ Coulomb/liter atm Joule.}$$

Although because of the very low noise level of an ionization chamber such a low signal can be detected this would require elaborate and expensive electronics.

An interesting variance of the ionization chamber is the "Panofsky coax." A large diameter gas-insulation coax strung the full circumference around the ring can be used as a continuous ionization chamber. The propagation time of the signal along the coax from the point of generation to the point of detection will give the location of beam loss. Such a scheme, ingenious as it is, suffers even more serious limitations in sensitivity and response time. Furthermore, for simultaneous beam losses at several locations, the electronics required to sort them out will have to be rather elaborate.

B. Photomultiplier-Scintillator

Inexpensive photomultiplier tubes (such as 931A) have been used at Cornell and PPA as radiation detectors. The response times of these tubes are in the nanosecond range. The response time of such a detector is, therefore, limited only by that of the electronics. The sensitivity is much higher than that of ionization chambers. Again, based on measurements made at the ZGS and on the experience of PPA and Cornell for our geometry the sensitivity of such a tube coupled to a plastic scintillator or immersed in liquid scintillator is of the order:

$$q \sim 10^{-7} \text{ Coulomb/Joule of beam on target.}$$

The sensitivity varies a great deal (as much as a factor of 5) from tube to tube. For our application, however, this variation in sensitivity should not be a concern.

Compared to the ionization chamber, the noise level of a photomultiplier tube is high. The "dark current" in these tubes is typically in the 10^{-8} A range. Nevertheless, as indicated above for our application, the signal is rather strong and the signal-to-noise ratio is quite good.

The photomultiplier tube is also susceptible to radiation damage. The predominant effect of radiation damage is the darkening of the glass. However, in the main ring with an average loss of no more than 10^{-3} of the design beam the photomultiplier tube can be expected to have a useful life of several years.

Conclusions

A. For all beam-loss mechanisms except E.2., the radiation is localized to about 1 cell length of the ring circumference. In principle one detector per ministraight is adequate. But it is useful to know the dropoff of the radiation level along the cell length. Therefore, it is desirable to place one detector in every drift space between magnets, at least for 2 or 3 cells downstream of (a) all medium straight sections (aperture blocks), (b) the injection-extraction long straight section (injection septum and kicker magnets, and extraction septa), and (c) the abort-scraper long straight section (beam stoppers of the abort and scraper systems).

The exact locations of the detectors in the drift spaces are not critical but the detectors should be placed as close to the beam as is convenient.

B. The best choice of detector is the photomultiplier-scintillator (e.g. the 931A tube immersed in liquid scintillators). Presumably a number of tubes can share a common voltage supply.

The signals should be integrated, and the integrated signals can either be observed individually throughout a complete accelerator cycle or be scanned by the time multiplex system.

C. For all beam-loss mechanisms except A.2. a microsecond response time is adequate. Since for photomultipliers the response time is limited only by that of the electronics, microsecond electronics should be used. A few detectors with nanosecond electronics placed downstream of the injection kicker magnet will take care of A.2.

The electronics should be capable of measuring less than 10^{-7} Coulomb from the photomultiplier. This enables the detector to detect about 1 Joule of beam loss corresponding to about 10^9 protons at injection or about 3×10^7 protons at 200 BeV.

Acknowledgement

The information on radiation detectors was supplied by M. Awschalom, R. Shafer, H. Edwards, and D. Edwards.